

# Production of Light Nuclei in Heavy Ion Collisions Within Multiple Freezeout Scenario

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## Abstract

We discuss the production of light nuclei in heavy ion collisions within a multiple freezeout scenario. Thermal parameters extracted from the fits to the observed hadron yields are used to predict the multiplicities of light nuclei. Ratios of strange to non strange nuclei are found to be most sensitive to the details of the chemical freezeout. The well known disagreement between data of  ${}^3_{\Lambda}\text{H}/{}^3\text{He}$  and  $\overline{{}^3_{\Lambda}\text{H}}/\overline{{}^3\text{He}}$  at  $\sqrt{s_{NN}} = 200$  GeV and models based on thermal as well as simple coalescence using a single chemical freezeout surface goes away when we let the strange and non strange hadrons freezeout at separate surfaces. At the LHC energy of  $\sqrt{s_{NN}} = 2700$  GeV, multiple freezeout scenario within a thermal model provides a consistent framework to describe the yields of all measured hadrons and nuclei.

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Hadron resonance gas models have been traditionally employed to understand the production of hadrons in heavy ion collisions across beam energies varying by several orders of magnitudes. This is done with a few thermal parameters like volume  $V$ , temperature  $T$  and chemical potentials  $\mu_B$ ,  $\mu_Q$  and  $\mu_S$  corresponding to the conserved charges (in QCD) baryon number  $B$ , electric charge  $Q$  and strangeness  $S$  respectively that describe the thermal state of the fireball at the time of chemical freezeout (CFO). By comparing the hadron yields to the thermal model predictions, the thermodynamic state of the fireball can be deduced at the time of CFO. The standard practice has been to assume a single freezeout surface for all hadrons which we call here 1CFO [1–3]. The recent LHC data on hadron yields at  $\sqrt{s_{NN}} = 2700$  GeV, particularly ratios of strange to non strange baryons like  $\Lambda/p$ ,  $\Xi/p$  and  $\Omega/p$  could not be explained by thermal models with 1CFO [4]. This has initiated new efforts in understanding the hadrochemistry at the time of chemical freezeout. In Refs. [5–7], the effects of late stage hadronic inelastic scattering was computed that mainly led to proton-antiproton annihilation resulting in better agreement with data. There has been suggestion to introduce non-equilibrium phase space factors for light and strange quarks [8] which also lead to agreement with data. In Refs. [9, 10] it was argued on the basis of hadrochemistry that non strange and strange hadrons are expected to freezeout at different times (2CFO). It was demonstrated that thermal model fits to hadron yields based on 2CFO improve considerably specially at the LHC energy [9]. From the microscopic point of view, because of the varying hadronic cross sections among the various hadrons in the medium, a sequential freezeout is expected to happen. In this paper we study the production of light nuclei in heavy ion collisions within 2CFO.

Recently STAR has reported the first observation of antihypernuclei at  $\sqrt{s_{NN}} = 200$  GeV [11]. While hypernuclei has been observed earlier, antihypernuclei have been elusive for a long time. Previous studies have found that at  $\sqrt{s_{NN}} = 200$  GeV, thermal and simple coalescence models with 1CFO describe antinuclei to nuclei ratios as well as ratios of non strange or strange nuclei like  ${}^3\overline{\text{He}}/{}^3\text{He}$ ,  ${}^3\overline{\Lambda}\text{H}/{}^3\Lambda\text{H}$ ,  ${}^3\text{He}/\text{H}$ ,  $\text{d}/\text{p}$  etc. On the other hand in the case of mixed ratios (strange to non strange nuclei ratios) like  ${}^3\Lambda\text{H}/{}^3\text{He}$  and  ${}^3\overline{\Lambda}\text{H}/{}^3\overline{\text{He}}$ , 1CFO is found to underpredict at the top STAR energy of  $\sqrt{s_{NN}} = 200$  GeV [12, 13]. In this paper we investigate the production of nuclei yields within 2CFO and show that in thermal as well as simple coalescence models, strange to non strange nuclei ratios demonstrate the necessity of 2CFO model over 1CFO.

The production of light nuclei in heavy ion collisions has been successfully studied within two phenomenological models with very different mechanism. Thermal models that successfully describe the hadron yields are even found to explain nuclei yields based on early stage production of the nuclei at the CFO surface along with the other hadrons. It was first pointed out in Refs. [14, 15] that light nuclei could also equilibrate chemically along with other hadrons in the expanding fireball produced in heavy ion collisions. Thus, there has been analysis of light nuclei yields based on thermal models with 1CFO which has been quite successful in describing their multiplicity [12, 13, 16, 17]. However, a detailed study of the effect of the small binding energy (compared to the fireball temperature) and reaction kinetics can not be investigated in such models. Secondly, coalescence models where there is late stage production by recombination of the constituent hadrons near the kinetic freezeout (KFO) surface can also describe the production of light nuclei. These require proper ways to incorporate correlations between the constituent hadrons in their phase spaces so that they could coalesce to form nuclei [18–31]. In both the scenarios, the CFO surface plays a crucial role. While in thermal models, the details of the CFO enter as the thermal parameters of the light nuclei themselves, in the case of the coalescence viewpoint they enter through the thermal parameters of the constituents. The aim of this work is to demonstrate the role played by the CFO scheme that one employs in determining the light nuclei yields both in thermal as well as coalescence models. For our purpose it is sufficient to restrict to the simplest version of the coalescence model where effects due to non trivial correlations in the phase space of the hadrons that coalesce to form nuclei are ignored. For the same reason, in the simple coalescence model we will only deal with ratios of nuclei while in the thermal model we will compute the yields in addition to the ratios of nuclei.

We compute the thermal as well as coalescence model predictions for different ratios of nuclei at different  $\sqrt{s_{NN}}$  using the thermal parameters extracted at the corresponding energies from fits to hadron yields within 2CFO [9]. Particularly at  $\sqrt{s_{NN}} = 200$  GeV, we study the sensitivity of the 2CFO parameters on light nuclei yields by including the available data on light nuclei in our fit. We also find a consistent description of all the measured hadron and nuclei yields at  $\sqrt{s_{NN}} = 2700$  GeV. The paper is organised as follows: In Section I we briefly discuss details of the 2CFO scheme as implemented in the thermal and coalescence models. In Section II we will present the model prediction for ratios of nuclei as obtained in the 2CFO scheme and compare them with that of 1CFO. We point out that amongst different nuclei ratios, mixed ratios (strange to non strange nuclei) are particularly suitable to probe and discriminate between different CFO schemes. At  $\sqrt{s_{NN}} = 200$  GeV, very good agreement between model prediction and data is found for the mixed ratios  ${}^3\Lambda\text{H}/{}^3\text{He}$  and  ${}^3\overline{\Lambda}\text{H}/{}^3\overline{\text{He}}$  within the 2CFO scheme. We find that thermal model with 2CFO provides a consistent picture that describes the yield of all measured hadron and nuclei yields at the LHC Pb-Pb collision at  $\sqrt{s_{NN}} = 2.76$  TeV. Finally in Section III we summarise and conclude.

## I. 2CFO SCHEME

### A. THERMAL MODEL

The ideal hadron resonance gas (HRG) partition function  $Z$  in the grand canonical ensemble at the time of CFO at a particular beam energy  $\sqrt{s_{\text{NN}}}$  is given as

$$\log [Z(\sqrt{s_{\text{NN}}})] = \sum_i \log [Z_i(T_i(\sqrt{s_{\text{NN}}}), \mu_i(\sqrt{s_{\text{NN}}}), V_i(\sqrt{s_{\text{NN}}}))] \quad (1)$$

where  $Z_i$  is the partition function of the  $i$ th hadron species and  $T_i$ ,  $\mu_i$  and  $V_i$  are its relevant thermal parameters at the time of CFO. Thus the primordial yield  $N_i^{\text{P}}$  of the  $i$ th hadron is given by

$$\begin{aligned} N_i^{\text{P}} &= \frac{\partial}{\partial \left(\frac{\mu_i}{T_i}\right)} \log [Z] \\ &= \frac{V_i T_i}{\pi^2} g_i m_i^2 \sum_{l=1}^{\infty} (-a)^{l+1} l^{-1} K_2(l m_i/T_i) \times \exp(l(B_i \mu_{B_i} + Q_i \mu_{Q_i} + S_i \mu_{S_i})/T_i) \end{aligned} \quad (2)$$

where  $a = -1$  for bosons and 1 for fermions.  $m_i$  and  $g_i$  are the mass and degeneracy factor of the  $i$ th hadron and  $B_i$ ,  $Q_i$  and  $S_i$  are its conserved charges, namely baryon number, electric charge and strangeness respectively. Here  $K_2$  is the Bessel function of the second kind. The total yield of the  $i$ th hadron  $N_i^{\text{t}}$  comprise of the primordial yield as well as feeddown from heavier resonances that decay to it

$$N_i^{\text{t}} = N_i^{\text{P}} + \sum_j N_j^{\text{P}} \times \text{B.R.}_{j \rightarrow i} \quad (3)$$

where  $\text{B.R.}_{j \rightarrow i}$  is the branching ratio of the channel in which the  $j$ th hadron decays to the  $i$ th hadron taken from P.D.G. [32]. In 1CFO, there is a single chemical freezeout surface and hence  $T_i(\sqrt{s_{\text{NN}}}) = T(\sqrt{s_{\text{NN}}})$  for all hadrons. Similarly,  $V_i$ ,  $\mu_{B_i}$ ,  $\mu_{Q_i}$  and  $\mu_{S_i}$  are same for all hadrons. In 2CFO, all strange hadrons and those with hidden strangeness freezeout at the same surface while the rest of the non strange hadrons freezeout at a separate surface. Thus  $T_i = T_{\text{ns}}$  for all non strange hadrons while  $T_i = T_{\text{s}}$  for all strange hadrons and those with hidden strangeness content. Volume and chemical potentials are also treated similarly. Within this framework, hadron yields were fitted and thermal parameters extracted for  $\sqrt{s_{\text{NN}}} = 6.27 - 2700$  GeV in Ref. [9]. While the extracted fugacity factors for both the surfaces are similar with the exception at low beam energies  $\sqrt{s_{\text{NN}}} < 10$  GeV, the temperature and volume parameters clearly signal separation of CFO for non strange and strange hadrons at all energies [9].

### B. COALESCENCE MODEL

Within this picture, the nuclei are modelled to form by coalescence of hadrons near the KFO surface. This is usually expressed in terms of the invariant coalescence factor  $B_A$

$$E_A \frac{d^3 N_A}{d^3 P_A} = B_A \left( E_p \frac{d^3 N_p}{d^3 P_p} \right)^Z \left( E_n \frac{d^3 N_n}{d^3 P_n} \right)^{A-Z} \quad (4)$$

where  $A$  and  $Z$  are the mass number and atomic number of the nuclei respectively. Depending on the choice of  $B_A$ , i.e. the mechanism in which one takes into account the hadronic correlations in the phase space at the final stages of the fireball evolution near KFO, there are various variants of the coalescence model [18–31].

A similar relation as Eq. 4 at the level of yields can be written down

$$N_A = C_A (N_p)^Z (N_n)^{A-Z} \quad (5)$$

where the details of phase space correlations are encoded into  $C_A$ . Thus, ratio of anti nuclei to nuclei yields can be expressed in terms of ratios of their corresponding constituent hadrons

$$\frac{\overline{N}_A}{N_A} = C_{\overline{A}A} (N_{\overline{p}}/N_p)^Z (N_{\overline{n}}/N_n)^{(A-Z)} \quad (6)$$

$$\sim C_{\overline{A}A} (N_{\overline{p}}/N_p)^A \quad (7)$$

where  $C_{\bar{A}A} = C_{\bar{A}}/C_A$ . From Eq. 6 to Eq. 7 we assume  $N_p \sim N_n$ . Although Eqs. 4, 5, 6 and 7 have been written for a nuclei containing only non strange hadrons like neutrons and protons as constituents, similar relation can be also written for hypernuclei containing strange hadrons like  $\Lambda$ .

Thus nuclei production in the coalescence model is a combination of two distinct physics issues: (a) the physics of  $C_{\bar{A}A}$  which is a subject of intense current research and an agreement over its correct interpretation is yet to be reached [22]. This is related to the correlation effects in the phase space that exist between the constituent hadrons at the time of the KFO, and (b) the abundances of the constituent hadrons at the time of KFO which is already fixed at the CFO surface obtained from fits to the hadron yields. In this paper we are interested in the role played by the latter physics in determining the nuclei yields. Hence we will consider the simplest version of the coalescence model in which we will take  $C_{\bar{A}A} = 1$  [13]. This will be sufficient for our purpose to demonstrate the dependence of the nuclei production on the CFO scheme.

## II. RESULTS

We will now present our results on the production of light nuclei and compare between 1CFO and 2CFO. Except pions, for all other hadrons and light nuclei,  $m/T \gg 1$  and hence we can keep only the  $l = 1$  term in Eq. 2 which is the Boltzmann approximation to get

$$N_i^p = \frac{V_i T_i}{\pi^2} g_i m_i^2 K_2(m_i/T_i) \times \exp((B_i \mu_{B_i} + Q_i \mu_{Q_i} + S_i \mu_{S_i})/T_i) \quad (8)$$

Now using the asymptotic expansion  $K_n(z) \sim \sqrt{\frac{\pi}{2z}} \exp(-z)$  and neglecting the resonance feeddown, we have for ratio

$$\begin{aligned} N_i^t/N_j^t &= \frac{g_i V_i}{g_j V_j} \left( \frac{T_i m_i}{T_j m_j} \right)^{3/2} \exp(m_j/T_j - m_i/T_i) \exp(B_i \mu_{B_i}/T_i - B_j \mu_{B_j}/T_j) \times \\ &\quad \exp(Q_i \mu_{Q_i}/T_i - Q_j \mu_{Q_j}/T_j) \exp(S_i \mu_{S_i}/T_i - S_j \mu_{S_j}/T_j) \end{aligned} \quad (9)$$

From Eq. 9, we can write for strange to non strange particle ratios in the thermal model

$$(N_i^t/N_j^t)^{\text{th}} = \exp(S \mu_S/T_s) \frac{g_i V_s}{g_j V_{ns}} \left( \frac{T_s m_i}{T_{ns} m_j} \right)^{3/2} \exp(m_j/T_{ns} - m_i/T_s) \exp(\mu_{B_s}/T_s - \mu_{B_{ns}}/T_{ns}) \quad (10)$$

Now lets turn our attention to the coalescence model. For definiteness, we first look at  ${}^3_\Lambda\text{H}/{}^3\text{He}$ . Modifying Eq. 7 suitably to take care of the  $\Lambda$  in  ${}^3_\Lambda\text{H}$ , we get for the ratio  ${}^3_\Lambda\text{H}/{}^3\text{He}$  in the coalescence model

$$({}^3_\Lambda\text{H}/{}^3\text{He})^c = (\Lambda/p)^{\text{th}} \quad (11)$$

Similarly, for  $\overline{{}^3_\Lambda\text{H}/{}^3\text{He}}$  we get

$$(\overline{{}^3_\Lambda\text{H}/{}^3\text{He}})^c = (\overline{\Lambda/p})^{\text{th}} \quad (12)$$

Here  $({}^3_\Lambda\text{H}/{}^3\text{He})^c$  and  $(\overline{{}^3_\Lambda\text{H}/{}^3\text{He}})^c$  refer to the nuclei ratios  $({}^3_\Lambda\text{H}/{}^3\text{He})$  and  $(\overline{{}^3_\Lambda\text{H}/{}^3\text{He}})$  respectively in the coalescence model. Thus, from Eqs. 10, 11 and 12 we conclude that both in thermal as well as coalescence models when we consider strange to non strange light nuclei ratios, there is an additional prefactor in 2CFO depending on the different freezeout volumes and temperatures of the strange and non strange hadrons apart from the usual Boltzmann and fugacity factors that arise in 1CFO. This is a very general result in 2CFO and is also true for strange to non strange hadron ratios like  $\Lambda/p$ . This makes such ratios quite sensitive probes to 2CFO. As we will see later in Fig. 4, this leads to agreement between data and 2CFO prediction of the ratios  $({}^3_\Lambda\text{H}/{}^3\text{He})$  and  $(\overline{{}^3_\Lambda\text{H}/{}^3\text{He}})$  which earlier studies [12, 13] based on 1CFO failed to explain. This is the main result of our paper.

From Eqs. 10, 11 and 12 we may write

$$({}^3_\Lambda\text{H}/{}^3\text{He})^{\text{th}} / ({}^3_\Lambda\text{H}/{}^3\text{He})^c = \left( \frac{m_{\Lambda}^3 m_p}{m_{\Lambda} m_{^3\text{He}}} \right)^{3/2} \exp((m_{^3\text{He}} - m_p)/T_{ns} - (m_{^3_\Lambda\text{H}} - m_{\Lambda})/T_s) \quad (13)$$

$$\simeq (1/3 + 2/3(m_p/m_{\Lambda}))^{3/2} \exp\left(\frac{2m_p\left(1 - \frac{T_{ns}}{T_s}\right)}{T_{ns}}\right) \quad (14)$$

From Eq. 13 to 14 we have used the fact that binding energy of  ${}^3_\Lambda\text{H}$  and  ${}^3\text{He}$  can be neglected compared to the nuclei masses as well as the fireball temperatures at the two freezeout surfaces. Here we would like to make few observations. If we put  $T_{ns} = T_s = T$ , we recover the result as expected in 1CFO [13]. Secondly, since the factor  $(1/3 + 2/3(m_p/m_\Lambda))^{3/2} \sim 0.85$ , in case of 1CFO the thermal value would be always smaller than that in the coalescence case [13]. However in 2CFO because of the additional exponential factor, depending on the value of  $T_{ns}/T_s$  as extracted from fits to hadron yields, the thermal value could be lesser or more than the coalescence value. In Fig. 1, we have plotted the particle ratios  $({}^3_\Lambda\text{H}/{}^3\text{He})^{\text{th}}$  and  $(\overline{{}^3_\Lambda\text{H}}/\overline{{}^3\text{He}})^{\text{th}}$  as well as  $(\Lambda/p)^{\text{th}}$  ( $=({}^3_\Lambda\text{H}/{}^3\text{He})^{\text{c}}$ ) and  $(\overline{\Lambda}/\overline{p})^{\text{th}}$  ( $=(\overline{{}^3_\Lambda\text{H}}/\overline{{}^3\text{He}})^{\text{c}}$ ) versus  $\sqrt{s_{\text{NN}}}$ . We find that within the uncertainties due to the errors in the fit parameters, thermal and coalescence values for the ratios agree. Thus as in 1CFO, it is not possible to discriminate between thermal and coalescence mechanism of nuclei production in 2CFO. However, the bands for 1CFO and 2CFO are quite distinct and hence they are good candidates to distinguish between the different freezeout scenarios. Currently the bands are based on the errors in the extraction of the thermal parameters from hadron yields [9], many of which are based on preliminary data from Beam Energy Scan (BES) programme of STAR [33]. We expect the bands to get narrower in the future with the availability of final data from BES. It is to be noted that the weak decay contribution from  $\Lambda$  to proton is treated differently for different experiments. While the STAR data for proton includes the weak decay contribution from  $\Lambda$  [34–40], data from NA49 [41–47], PHENIX [48–50] and ALICE [51] are corrected from such decays. We note from Fig. 1 that broadly speaking, while  $\Lambda/p$  and  ${}^3_\Lambda\text{H}/{}^3\text{He}$  rise and then saturate with increasing  $\sqrt{s_{\text{NN}}}$ ,  $\overline{\Lambda}/\overline{p}$  and  $\overline{{}^3_\Lambda\text{H}}/\overline{{}^3\text{He}}$  first fall and then stay unchanged with increasing  $\sqrt{s_{\text{NN}}}$  (at lower energies they are expected to go to zero as  $\Lambda$  ( $\overline{\Lambda}$ ) is heavier than  $p$  ( $\overline{p}$ )). Thus the different shapes of  $\Lambda/p$  ( ${}^3_\Lambda\text{H}/{}^3\text{He}$ ) and  $\overline{\Lambda}/\overline{p}$  ( $\overline{{}^3_\Lambda\text{H}}/\overline{{}^3\text{He}}$ ) can be attributed to the strange fugacity factor  $\exp(S\mu_S/T)$ . With decreasing  $\sqrt{s_{\text{NN}}}$  as  $\mu_S$  increases, the strange fugacity factor enhances the difference between 1CFO and 2CFO for  $\overline{\Lambda}/\overline{p}$  since  $\overline{\Lambda}$  has  $S = 1$ . The effect of the strange fugacity factor is just the opposite on  $\Lambda/p$  as  $\Lambda$  has  $S = -1$ . As seen from Fig. 1, at the FAIR energy range this makes  $\overline{\Lambda}/\overline{p}$  and  $\overline{{}^3_\Lambda\text{H}}/\overline{{}^3\text{He}}$  excellent candidates to distinguish between 1CFO and 2CFO freezeout scenarios. However, it has to be kept in mind that at the FAIR the production of antibaryons will be highly suppressed due to large baryon chemical potential.

Eq. 9 gets further simplified if we consider ratios of particles with same flavor like  $d/p$ ,  ${}^3_\Lambda\text{H}/\Lambda$  or those involving antiparticles like  $\overline{d}/\overline{p}$ ,  $\overline{{}^3\text{He}}/\overline{{}^3\text{He}}$  etc.

$$N_i^t/N_j^t = \left(\frac{g_i}{g_j}\right) \left(\frac{m_i}{m_j}\right)^{3/2} \exp(((m_j - m_i) + (B_i - B_j)\mu_B + (Q_i - Q_j)\mu_Q + (S_i - S_j)\mu_S)/T) \quad (15)$$

In this case the prefactor that arose in the earlier case drops out. Hence we expect similar predictions for 1CFO and 2CFO. We have plotted some of these ratios in Fig. 2. As expected the bands for 1CFO and 2CFO almost overlap across the entire beam energies.

For anti-particle to particle ratios, Eq. 15 simplifies even further. Except the fugacities, all other factors drop out. Thus from Eqs. 7 and 15 we may write

$$\left(\overline{N_i^t}/N_i^t\right)^{\text{c}} = \left(\overline{N_i^t}/N_i^t\right)^{\text{th}} = \exp(-2(B_i\mu_{B_i} + Q_i\mu_{Q_i} + S_i\mu_{S_i})/T) \quad (16)$$

Thus one can directly extract the fugacity factors using such ratios. Since nuclei have  $B > 1$ , anti nuclei to nuclei ratios are even more sensitive to the baryon fugacity factor compared to that of hadrons [12, 13]. However as expected from Eq. 16, these ratios are not sensitive to the different freezeout schemes. We have plotted in Fig. 3 a few anti-particle to particle ratios, namely  $\overline{p}/p$ ,  $\overline{\Lambda}/\Lambda$ ,  $\overline{d}/d$ ,  $\overline{{}^3\text{He}}/{}^3\text{He}$  and  $\overline{{}^4\text{He}}/{}^4\text{He}$  versus  $\sqrt{s_{\text{NN}}}$ . The error bands have not been shown due to clarity.

So far we have analysed several light nuclei ratios as function of  $\sqrt{s_{\text{NN}}}$ . We have plotted these ratios for 1CFO and 2CFO freezeout schemes. We argued as well as demonstrated that ratios of hadrons and nuclei with same flavor are insensitive to these different freezeout schemes. Similarly, while ratios of anti nuclei to nuclei are known to be very sensitive to the baryon fugacity factor, they are not suitable to distinguish between the different freezeout schemes, 1CFO and 2CFO. However, we showed that ratios of strange to non strange hadrons and nuclei can discriminate between the different freezeout schemes. Moreover, we argued that even if we change the production mechanism from thermal to a simple coalescence, the above statement on the sensitivity of the various types of nuclei ratios on the CFO scheme remain true. This completes our study of the light nuclei production for different freezeout schemes over a broad range of  $\sqrt{s_{\text{NN}}}$ . Now we will focus on the following beam energies:  $\sqrt{s_{\text{NN}}} = 200$  and 2700 GeV. At these energies, data for a large number of hadrons as well as light nuclei including strange nuclei like  ${}^3_\Lambda\text{H}$  are available inviting for a more detailed inspection.

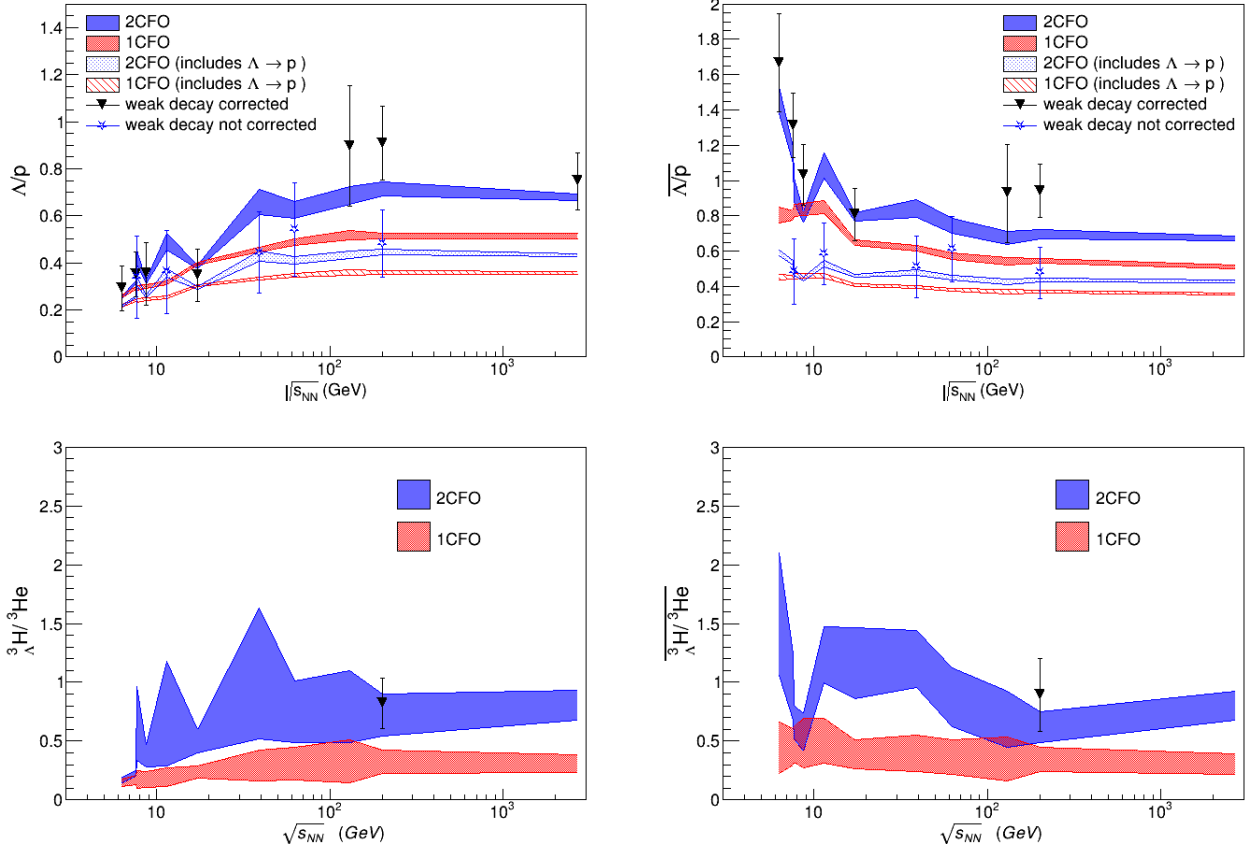


FIG. 1. (Color online) Plots of ratios of strange to non strange particles versus  $\sqrt{s_{NN}}$ . The blue bands correspond to 2CFO and red bands to 1CFO. The width of the bands reflect the uncertainties associated with the ratios extracted in thermal model. The solid inverted triangle and open stars represent the experimentally measured ratios [11, 34–51].

$\sqrt{s_{NN}}$ (GeV)	nuclei fitted	$10^4 V_S$ (MeV $^{-3}$ )	$10^4 V_{NS}$ (MeV $^{-3}$ )	$T_S$ (MeV)	$T_{NS}$ (MeV)	$\mu_S$ (MeV)	$\mu_{NS}$ (MeV)	$\chi^2/N_{df}$
200.	No	2.2 (0.4)	2.8 (0.8)	164 (3)	155 (6)	31 (11)	22 (16)	23/6
200.	Yes	2.3 (0.4)	2.6 (0.8)	163 (3)	155 (6)	27 (11)	23 (16)	24/10
2700.	No	5.5 (0.6)	9.7 (0.8)	158 (3)	145 (3)	0 (12)	0 (7)	3.1/6

TABLE I. The freezeout parameters in 2CFO at top RHIC energy of  $\sqrt{s_{NN}} = 200$  GeV and LHC energy of  $\sqrt{s_{NN}} = 2700$  GeV.

In Fig. 4, we have shown the results obtained at  $\sqrt{s_{NN}} = 200$  GeV. The fits of the results as shown in Table I are found to change little when we include even the light nuclei in the fits. It is found that 2CFO is able to correctly predict  ${}^3\text{H}/{}^3\text{He}$  ratio while 1CFO doesn't. There is mismatch with data in the strange baryon sector. The cause for this could be twofold: firstly a proper treatment of the weak decays in the STAR data set is necessary before anything conclusive can be said. Secondly, this could be a hint for further possible structures in the freezeout mechanism, for example, an early freezeout of the strange baryons. It is to be noted that including the strangeness undersaturation factor  $\gamma_S$  improves the agreement with data considerably in this case. The issue of the weak decays is much better addressed in ALICE. We have shown the fits to the latest (0–10) % ALICE data [53–56] in Fig. 5. The 2CFO mechanism seems to describe the data for all the particles including light nuclei unlike the 1CFO where the protons are not described well. In the future, the LHC experiment is also expected to produce more high precision data on nuclei which could provide more insight into the freezeout mechanism.

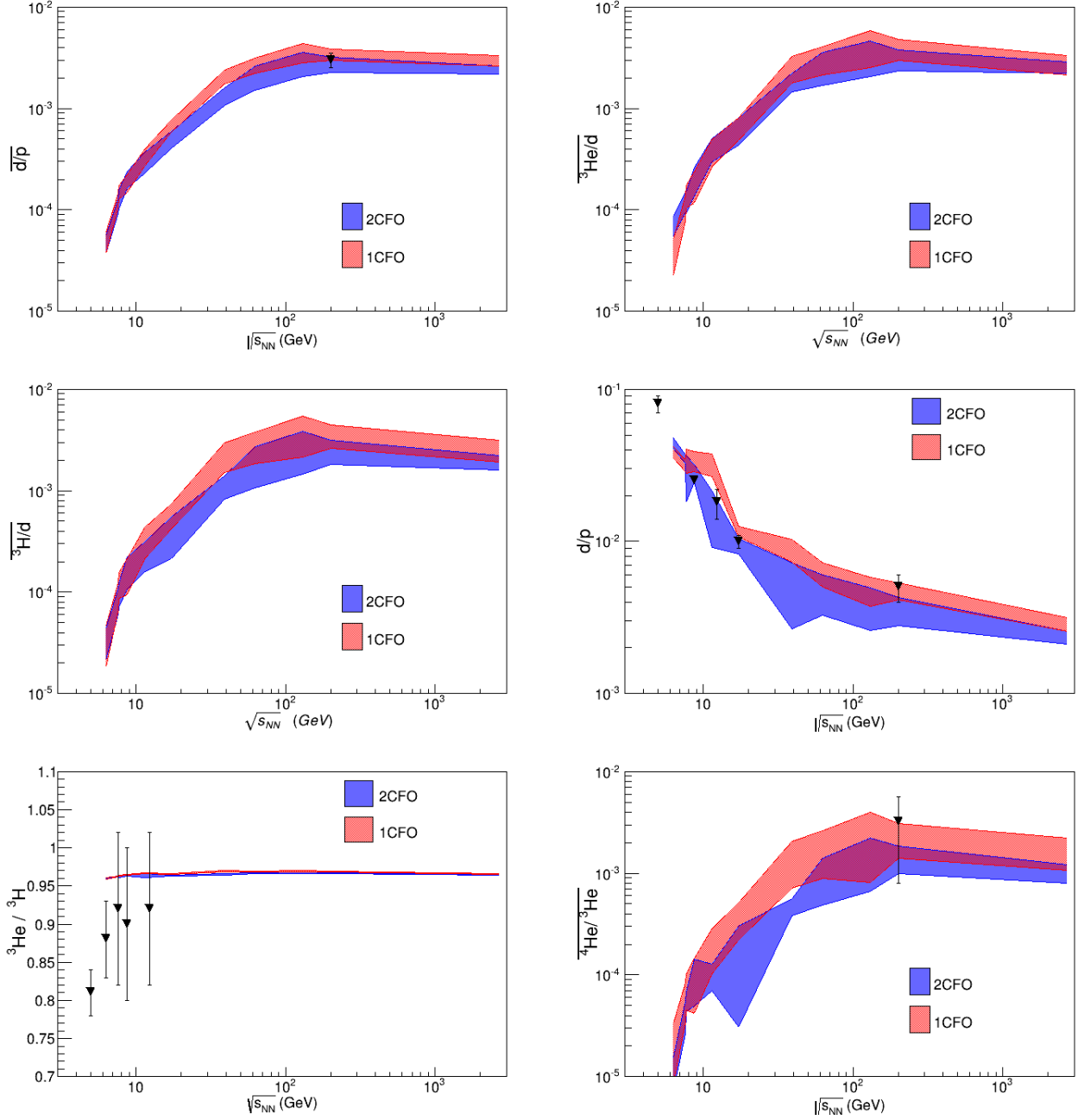


FIG. 2. (Color online) Plots of ratios of non strange particles versus  $\sqrt{s_{NN}}$ . The blue bands correspond to 2CFO and red bands to 1CFO. The width of the bands reflect the uncertainties associated with the ratios extracted in thermal model. The solid inverted triangles represent the experimentally measured ratios [11, 34–52].

### III. SUMMARY AND CONCLUSION

We have studied the production of light nuclei in heavy ion collisions within thermal and simple coalescence models in the light of multiple freezeout scenarios. We argued and showed that irrespective of the production mechanism, while ratios of same flavor nuclei (non strange or strange) are insensitive to the chemical freezeout scheme chosen,

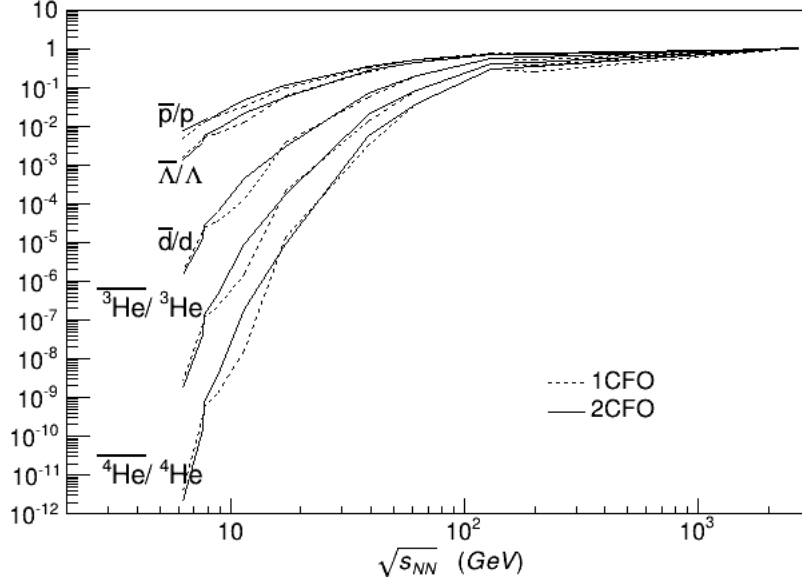


FIG. 3. Few antiparticle to particle ratios of light nuclei. As argued in the text, these ratios are not sensitive to the different freezeout mechanisms.

mixed ratios i.e. ratios of unlike flavor nuclei can probe the details of the chemical freezeout. This is in general true for hadrons also. Particularly at  $\sqrt{s_{NN}} = 200$  GeV, hitherto unexplained nuclei ratios  $\bar{\Lambda}^3\text{H}/^3\text{He}$  and  $\bar{\Lambda}^3\text{H}/^3\text{He}$  within the assumption of a single chemical freezeout surface, is found to agree with model predictions when we modify the chemical freezeout scheme such that strange and non strange hadrons freezeout separately. In the future, it would be interesting to investigate the effect of including in HRG yet undiscovered resonances that are predicted by lattice QCD as well as quark models on the above ratios [57].

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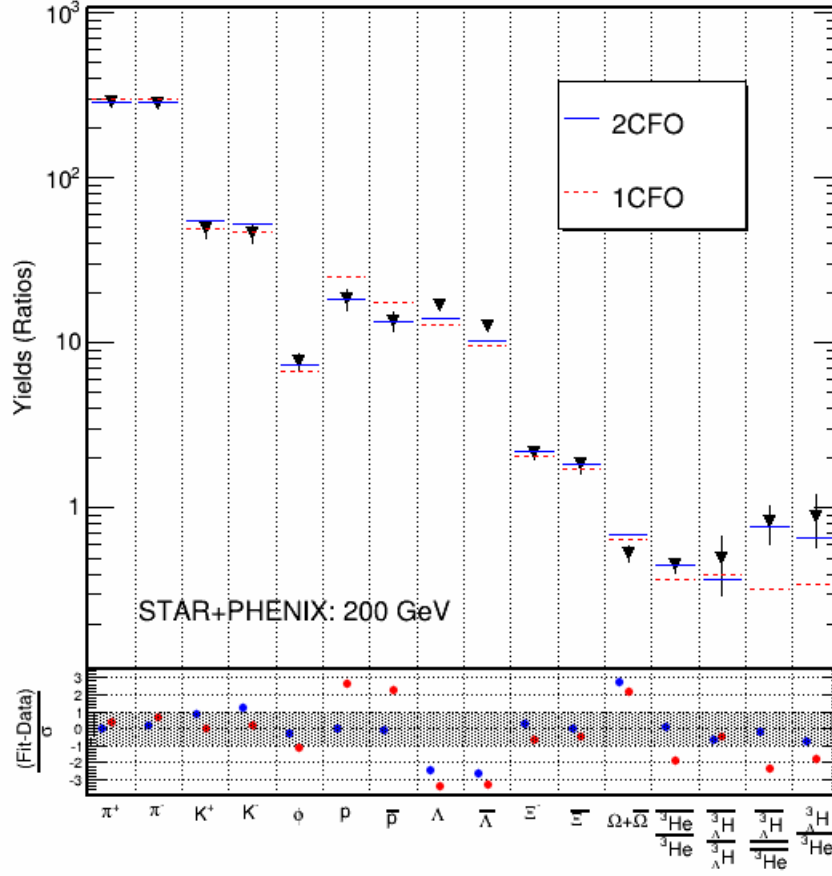


FIG. 4. (Color online) Thermal model production of hadrons and nuclei at  $\sqrt{s_{NN}} = 200$  GeV. Here  $\sigma$  is the error in the data. The solid inverted triangle represent the experimentally measured ratios [11, 34, 38–40]. Only the data of hadrons were used to extract the thermal parameters.

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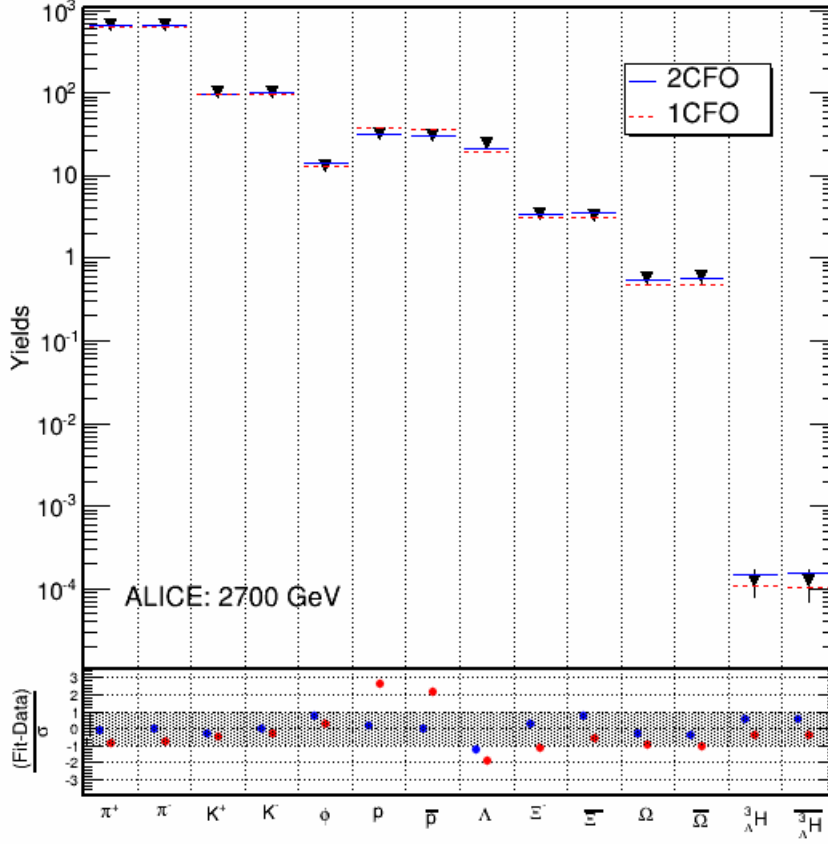


FIG. 5. (Color online) Thermal model production of hadrons and nuclei at  $\sqrt{s_{NN}} = 2700$  GeV. Here  $\sigma$  is the error in the data. The solid inverted triangle represent the experimentally measured ratios [53–56]. Only the data of hadrons were used to extract the thermal parameters.

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